Proceedings – 23rd Annual Conference – IEEE/EMBS Oct.25-28, 2001, Istanbul, TURKEY

REAL-TIME SIGNAL PROCESSING TECHNIQUES IN MRI

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***Abstract* - Due in part to the very high flexibility of image contrast, the applications of magnetic resonance imaging (MRI) continue to grow. Advances in data acquisition speed, as facilitated by MRI physics, have provided the motivation for specific real-time techniques. For useful and broad implementation this has required that real-time signal processing methods be used. In this work the principal elements of a real-time MRI system are reviewed, major signal processing techniques presented, and several contemporary applications discussed. Further improvements in computational speed will allow increased sophistication in real-time MRI techniques in the future.**

I. INTRODUCTION

Since the time of its initial development approximately 20 years ago, magnetic resonance imaging (MRI) has become a commonly used, widely accepted diagnostic medical imaging modality. Worldwide the installed base is over 10,000 systems, and approximately 100,000 patient examinations are performed per day. Although a number of clinical uses for MRI were identified early on, such as for imaging of the brain and spine, the applications of MRI have expanded considerably, such as for imaging of the musculoskeletal and cardiovascular systems. Over this 20 year timeframe MRI has also undergone considerable technical development, with major advances in the MRI hardware as well as the manner in which the data are collected and images formed.

Compared to other medical imaging modalities such as x-ray imaging and ultrasound, MRI in general has longer image acquisition times. Early "spin-echo" sequences required times as long as 10 minutes or more to obtain the data for a single cross-sectional "slice." In the last 15 years a number of advances in the MR imaging physics have allowed considerable reductions in this time. These include echo-planar imaging (initially developed in the 1970s [1] but shown as clinically feasible a decade later [2]), limited flip angle gradient echo imaging [3], multiple phase-encoded spin-echo imaging (sometimes called RARE or fast-spin-echo) [4]. Many variants of these techniques have also been developed.

As the acquisition times have been progressively reduced in MRI, so has the manner in which MRI is used clinically been expanded. For example, the ability to obtain high quality images within a 20 second time interval allows acquisition during breathholding, and this can allow imaging of the thorax and abdomen without the image degradation due to respiration.

Additional distinguishing characteristics of MRI compared to other modalities are the highly variable contrast as well as the ability to image slices of arbitrary size and orientation. This high degree of flexibility in image appearance, coupled with the ability to acquire images in decreasingly smaller times, has raised the possibility of allowing the user to perform MR imaging on an interactive basis. In principle this can allow the user to view the anatomy of interest in real time and adjust the scanning parameters in a manner specific to the patient. To do this effectively requires real-time processing of the MR-related signals at various steps in the image formation process.

II. SYSTEM OVERVIEW

The term "real time" can be interpreted many different ways in considering imaging systems, generally in terms of number of images per second. In this work this is not specified as some fixed number, but rather it is assumed that the process of data acquisition and image formation is matched to the time scale of the phenomenon under study.

Real-time MRI systems are comprised of three major elements: (i) a high speed data acquisition method; (ii) means for reconstruction of the data into an image; and (iii) means for alteration of the data acquisition on the basis of the reconstructed data.

The first of these, data acquisition, is determined by the MRI physics. A specific pulse sequence is used, such as the above-mentioned echo-planar, gradient echo, or fast-spin-echo, as dictated by the desired image contrast, spatial resolution, and immunity to various artifacts. The acquisition times for continuous imaging of an individual slice can be the order of several tens of msec for echo-planar methods, hundred msec for gradient echo, and one second for fast-spin-echo techniques. An additional possibility is the imaging of a single line or pencil through the subject, and this can be done at rates as high as 50 Hz [5]. Alternatively, it is possible to image along a simple k-space trajectory, such as a circle [6], in order to determine specific information for some application. Details of many of the contemporary pulse sequences which can be used for the high speed imaging in general are provided in the recent literature [7].

Images need to be reconstructed in MRI because the data acquisition actually samples the spatial frequency spectrum or the Fourier-transformed representation of the image rather than the image itself. A single MR signal, such as a measurement comprising 256 points sampled over a 4 msec time interval, typically samples one line of the Fourier transform space. The number of lines sampled of this space, proportional to the total number of Fourier terms measured,

Report Documentation Page

Report Date	Report Type	Dates Covered (from... to)
25OCT2001	N/A	-

Title and Subtitle Real-Time Signal Processing Techniques in MRI	**Contract Number**
	Grant Number
	Program Element Number
Author(s)	**Project Number**
	Task Number
	Work Unit Number
Performing Organization Name(s) and Address(es) Magnetic Resonance Laboratory, Mayo Clinic, Rochester MN 55905	**Performing Organization Report Number**
Sponsoring/Monitoring Agency Name(s) and Address(es) US Army Research, Development & Standardization Group (UK) PSC 802 Box 15 FPO AE 09499-1500	**Sponsor/Monitor's Acronym(s)**
	Sponsor/Monitor's Report Number(s)
Distribution/Availability Statement Approved for public release, distribution unlimited	
Supplementary Notes Papers from the 23rd Annual International Conference of the IEEE Engineering in Medicine and Biology Society, 25-28 Oct 2001, held in Istanbul, Turkey. See also ADM001351 for entire conference on cd-rom.	
Abstract	
Subject Terms	
Report Classification unclassified	**Classification of this page** unclassified
Classification of Abstract unclassified	**Limitation of Abstract** UU
Number of Pages 4	

determines the spatial resolution of the image. The spacing between lines and samples is proportional to the inverse of the field of view in that direction.

The interactivity of real-time MRI is provided by allowing for adjustment of the MRI scanning parameters on the basis of the reconstructed image. Sometimes interactive adjustment is done by the operator, while in other instances it might be done automatically by an algorithmic-based interpretation of the current image or recent series of images. One practical example of operator control is allowance for interactive adjustment of the plane of section. This plane is determined by the specific waveforms applied to the magnetic gradients within the MRI pulse sequence. For example, it may be desirable to choose a slice which exactly cuts through the left ventricle of the heart, a so-called “short axis” view. The specific angulation varies from patient to patient. By interactively imaging and identifying structures of the heart the operator can direct the coordinates to a controller which in turn generates the rotation matrix applied to the gradient system.

III. HARDWARE FOR REAL-TIME MRI

In considering what hardware configuration to use for real-time digital signal processing in MRI there are a number of important technical specifications. Perhaps the first of these is speed, particularly the time required to perform a fast Fourier transform (FFT) because so much of MR image reconstruction is based on Fourier transformation. However, it is important to note that there are many mathematical processes of interest beyond FFTs. These include, for example, regridding algorithms [8], auto- and cross-correlations, determination of magnitude and phase at each pixel, high speed regression and curve fitting, and means for combining sub-images from separate coil elements. As microprocessor cycle frequencies have continued to increase in the last decade, a number of design approaches have been used successfully. These include systems in which the reconstruction is primarily performed using a dedicated array processor [9], one or more work stations [10], or an approach using special purpose computational hardware [11, 12]. Indeed, conceivably real-time reconstruction can be performed on contemporary, high clock speed personal computers.

In addition to processing speed, other important specifications include: (i) flexibility of the input port of the reconstruction system; (ii) system latency; and (iii) memory size and addressing. The first of these pertains to how readily the reconstruction system can accommodate data which may have been acquired using different sampling trajectories in Fourier transform or “k” space. For example, a one-dimensional 1024-point navigator echo may be acquired only several msec prior to a 512-point spiral-format image echo with an expectation that both be somehow reconstructed in real time. Within this short timeframe the system must be able to account for the different vector size and k-space format. System latency refers to time delays within the entire reconstruction process, possibly due to causes other than execution of the mathematical algorithm. One example is the delay, as might be due to data transfer, between the time of digitization of the data and the time at which the reconstruction of that data commences. Another possible latency is the time delay between completion of reconstruction of an image and the time that image is first displayed to the operator. Latency becomes particularly important when the initiation of some process depends critically upon what is observed in the reconstructed image sequence. One example of this is fluoroscopically-triggered contrast-enhanced MR angiography [13]. Memory size and addressing become particularly relevant for methods in which large amounts of data are accumulated for processing, such as functional neuro MRI and 3D imaging, or for techniques which use partial k-space updating. For research environments it is clearly desirable to have ease of programmability.

IV. APPLICATIONS OF REAL-TIME MRI

Real-time signal processing methods can be illustrated by a number of emerging applications.

A. MR Fluoroscopy

This term refers to continuous real-time MR imaging [14] as might be used to facilitate the setup or acquisition of high quality, diagnostic images. It is analogous to the use of x-ray fluoroscopy which serves a similar purpose in x-ray based imaging. In some sense this is the most direct application of real-time signal processing in that image reconstruction is performed as the data are acquired, and the operator contols the plane of section based on the sequence of displayed images. In an early demonstration with gradient echo acquisition the real-time capability was shown to reduce by almost an order of magnitude the time required to localize specific sections of the left ventricle [15]. Using spiral trajectories, imaging rates as high as 10 Hz have been achieved, and this has been used for cardiac imaging in patients who have been poor candidates for echocardiography [16].

B. Real-Time Navigator Echoes

The term “navigator” echo refers to an MR signal measured to monitor the motion of an object during the course of the acquisition of the image data [17]. It was originally designed to allow for the data to be retrospectively corrected for the motion measured [18]. With real-time processing techniques, however, it is possible to use the navigator echo to adjust the acquisition instantaneously, within msec of acquisition [19]. This can be useful for imaging of the heart, in which case it is necessary to account for both cardiac and respiratory motion. By restricting the data acquisition to the diastolic phase of the cardiac cycle, cardiac motion can be accounted for. By using a navigator echo to monitor the superior-inferior position of the diaphragm, this motion information can be used to include or reacquire the accompanying raw data or even to adjust the plane of excitation in an

attempt in an attempt to track the heart position. More recently navigator echoes are being acquired along specific circular trajectories in k-space, so-called orbital navigator echoes, in order to have a high degree of sensitivity to rotation [6]. These are being used in functional neuro MRI, a field which is particularly prone to error if the subject moves during the data acquisition. Initial implementation allowed for rotation about one axis [20], but more recently the allowance for multiaxial rotations is being measured and corrected in real time [21].

C. Real-Time Image-Triggered MR Angiography

A growing application in MRI is the imaging of blood vessels using an intravenously administered contrast agent [22]. Because of the wide range of transit times from patient to patient of the contrast bolus as it moves from the venous injection site to the arteries of interest, and because of the need to accurately time the MR acquisition to the arterial phase of the contrast bolus, it is necessary to determine proper timing on a patient-specific basis. One effective way to do this is real-time image or “fluoroscopically triggered” contrast-enhanced MR angiography [23]. With this technique good spatial resolution 2D images are acquired of the targetted arterial anatomy in real time at rates of 1-2 Hz after the contrast material has been injected. Upon visualization of contrast arrival in the targetted vessels, the operator triggers the very high resolution 3D scan by mouse click. This technique has proven to be highly reliable in capturing the desired arterial phase for blood vessels from the neck to the pelvis [24]. Real-time signal processing methods used are high speed reconstruction, interactive localization, and instantaneous switching between 2D and 3D pulse sequences.

D. Interactive Fast-Spin-Echo Imaging

Yet another emerging application of real-time MRI techniques is the use of RARE [4] or fast-spin-echo imaging on an interactive basis. When implemented as a single shot approach all of the desired k-space data are read out in one excitation cycle. Recently this method has been incorporated with real-time reconstruction and parameter control to allow interactive imaging [25]. As part of this, the technique of driven equilibrium has been used to maintain high SNR, even for TR times of 2000 msec or less, and Wiener demodulation has been incorporated to restore spatial resolution loss due to T2 modulation. The resultant interactive spin-echo method is currently being used in studies of the pelvic floor, for fetal imaging, and improved methods for MR cholangiopancreatography (MRCP).

V. DISCUSSION

Signal processing methods are critical in virtually all of the stages of the process of MRI data acquisition and image formation. As advances in MRI physics in the last two decades have permitted acquisition times for MR imaging to be progressively reduced from minutes to the order of seconds, it has become necessary to speed up the signal processing to make efficient use of the moe rapidly acquired data. Furthermore, real-time signal processing can permit specific applications of MRI which would not be possible otherwise. These are often designed to exploit the vast flexibility of contrast of MRI and to tune the acquisition on a patient-specific basis. As the range of applications continues to grow, particularly interactive MRI techniques, real-time signal processing will become even more sophisticated and common.

VI. CONCLUSION

Real-time MRI signal processing techniques are growing in importance in allowing expanded applications of MRI as well as improved reliability by allowance for patient-specific characteristics.

REFERENCES

[1] P. Mansfield, "Multi-planar image formation using NMR spin echoes," *J Phys C*, vol. 10, pp. L55, 1977.

[2] M. K. Stehling, A. M. Howseman, R. J. Ordidge, B. Chapman, R. Turner, R. Coxon, P. Glover, P. Mansfield, and R. E. Coupland, "Whole-body echo-planar MR imaging at 0.5T," *Radiology*, vol. 170, pp. 257-263, 1989.

[3] A. Haase, J. Frahm, D. Matthaei, W. Hanicke, and K. D. Merboldt, "FLASH imaging, rapid NMR imaging using low flip-angle pulses," *J Magn Reson*, vol. 67, pp. 258-266, 1986.

[4] J. Hennig, A. Nauerth, and H. Friedburg, "RARE imaging: a fast imaging method for clinical MR," *Magn Reson Med*, vol. 3, pp. 823-833, 1986.

[5] R. K. Butts, N. J. Hangiandreou, and S. J. Riederer, "Phase velocity mapping with a real time line scan technique," *Magn Reson Med*, vol. 29, pp. 134-138, 1993.

[6] Z. W. Fu, Y. Wang, R. C. Grimm, P. J. Rossman, J. P. Felmlee, S. J. Riederer, and R. L. Ehman, "Orbital navigator echoes for motion measurements in magnetic resonance imaging," *Magn Reson in Med*, vol. 34, pp. 746-753, 1995.

[7] M. T. Vlaardingerborek and J. A. den Boer, *Magnetic Resonance Imaging*. Berlin: Springer, 1999.

[8] J. D. O'Sullivan, "A fast sinc function gridding algorithm for Fourier inversion in computer tomography," *IEEE Trans Med Img*, vol. MI-4, pp. 200-207, 1985.

[9] R. C. Wright, S. J. Riederer, F. Farzaneh, P. J. Rossman, and Y. Liu, "Real-time MR fluoroscopic data acquisition and image reconstruction," *Magn Reson Med*, vol. 12, pp. 407-415, 1989.

[10] J. Pauly, A. Kerr, C. Hardy, C. Meyer, D. Nishimura, and A. Macovski, "Real-time dynamic imaging on a conventional whole-body imaging system," presented at 4th Mtg, Intl Soc Magn Reson Med, New York, 1996.

[11] A. F. Gmitro, A. R. Ehsani, T. A. Berchem, and R. J. Snell, "A real-time reconstruction system for magnetic resonance imaging," *Magn Reson Med*, vol. 35, pp.

734-740, 1996.

[12] V. Rasche, D. Holz, J. Kohler, R. Proska, and P. Roschmann, "Catheter tracking using continuous radial MRI," *Magn Reson Med*, vol. 37, pp. 963-968, 1997.

[13] A. H. Wilman, S. J. Riederer, B. F. King, J. P. Debbins, P. J. Rossman, and R. L. Ehman, "Fluoroscopically-triggered contrast-enhanced three-dimensional MR angiography with elliptical centric view order: application to the renal arteries," *Radiology*, vol. 205, pp. 137-146, 1997.

[14] S. J. Riederer, T. Tasciyan, F. Farzaneh, J. N. Lee, R. C. Wright, and R. J. Herfkens, "MR fluoroscopy: technical feasibility," *Magn Reson Med*, vol. 8, pp. 1-15, 1988.

[15] J. P. Debbins, S. J. Riederer, P. J. Rossman, R. C. Grimm, J. P. Felmlee, J. F. Breen, and R. L. Ehman, "Cardiac magnetic resonance fluoroscopy," *Magn Reson Med*, vol. 36, pp. 588-595, 1996.

[16] A. B. Kerr, J. M. Pauly, B. S. Hu, K. C. Li, C. J. Hardy, C. H. Meyer, A. Macovski, and D. G. Nishimura, "Real-time interactive MRI on a conventional scanner," *Magn Reson Med*, vol. 38, pp. 355-367, 1997.

[17] R. L. Ehman and J. P. Felmlee, "Adaptive technique for high definition MR imaging of moving structures," *Radiology*, vol. 173, pp. 255, 1989.

[18] H. W. Korin, F. Farzaneh, R. C. Wright, and S. J. Riederer, "Compensation for effects of linear motion in MR imaging," *Magn Reson Med*, vol. 12, pp. 99-113, 1989.

[19] Y. L. Liu, S. J. Riederer, P. J. Rossman, R. C. Grimm, J. P. Debbins, and R. L. Ehman, "A monitoring, feedback, and triggering system for reproducible breath-hold MR imaging," *Magn Reson Med*, vol. 30, pp. 507-511, 1993.

[20] C. C. Lee, C. R. Jack, R. C. Grimm, P. J. Rossman, J. P. Felmlee, R. L. Ehman, and S. J. Riederer, "Real-time adaptive motion correction in functional MRI," *Magn Reson Med*, vol. 36, pp. 436-444, 1996.

[21] H. A. Ward, S. J. Riederer, R. C. Grimm, R. L. Ehman, J. P. Felmlee, and C. R. Jack, "Prospective multiaxial motion correction in fMRI," *Magn Reson Med*, vol. 43, pp. 459-469, 2000.

[22] M. R. Prince, E. K. Yucel, J. A. Kaufman, D. C. Harrison, and S. C. Geller, "Dynamic gadolinium-enhanced 3D abdominal MR arteriography," *J Magn Reson Img*, vol. 3, pp. 877-881, 1993.

[23] A. H. Wilman, J. P. Debbins, P. J. Rossman, B. F. King, C. D. Johnson, R. L. Ehman, and S. J. Riederer, "Fluoroscopically-triggered contrast-enhanced three dimensional MR angiography," presented at 5th Mtg, Intl Soc Magn Reson in Med, Vancouver, 1997.

[24] S. J. Riederer, M. A. Bernstein, J. F. Breen, R. F. Busse, R. L. Ehman, S. B. Fain, T. C. Hulshizer, J. Huston, B. F. King, D. G. Kruger, and S. Shah, "Three-dimensional contrast-enhanced MR angiography with real-time fluoroscopic triggering: design specifications and technical reliability in 330 patient studies.," *Radiology*, vol. 215, pp. 584-593, 2000.

[25] R. F. Busse, S. J. Riederer, J. G. Fletcher, A. E. Bharucha, and K. R. Brandt, "Interactive fast spin-echo imaging," *Magn Reson Med*, vol. 44, pp. 339-348, 2000.